

SANDIA REPORT

SAND 2004-6438

Unlimited Release

Printed December 2004

P3 Microengine Development at Washington State University

Christopher Applett
Scott Whalen

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of Energy's
National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.



Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865)576-8401
Facsimile: (865)576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.osti.gov/bridge>

Available to the public from

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd
Springfield, VA 22161

Telephone: (800)553-6847
Facsimile: (703)605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: <http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online>



P3 Microengine Development at Washington State University

Christopher Apblett
Microdevice Technologies
Sandia National Laboratories
PO Box 5800
Albuquerque, NM 87185-0603

Scott Whalen
Washington State University
Pullman, WA

Abstract

There is a pressing need for miniaturized power systems for a variety of applications requiring a long life in the field of operations. Such power systems are required to be capable of providing power for months to years of operation, which all but eliminates battery technologies and technologies that bring their own fuel systems (except for nuclear fuel systems, which have their own drawbacks) due to constraints of having the all of the chemical fuel necessary for the entire life of the operational run available at the starting point of the operation. Alternatively, harvesting energy directly from the local environment obviates this need for bringing along all of the fuel necessary for operation. Instead, locally available energy, either in the form of chemical, thermal, light, or motion can be harvested and converted into electrical energy for use in sensor applications. The work from this LDRD is focused on developing a thermal engine that can take scavenged thermal gradients and convert them into direct electrical energy.

The converter system is a MEMS based external combustion engine that uses a modified Stirling cycle to generate mechanical work on a piezoelectric generator. This piezoelectric generator then produced an AC voltage and current that can be delivered into an external load. The MEMS engine works on the conversion of a two phase working fluid trapped between two deformable membranes. As heat is added to the

system, the liquid working fluid is converted to a gas, which exerts pneumatic pressure on the membranes, expanding them outward. This outward expansion continues after the heat input is removed when the engine is operated at resonance, since the membrane is expanded further due to inertial forces. Finally, the engine cools and heat rejection is accomplished through the membranes, closing the thermodynamic cycle. A piezoelectric generator stack is deposited on one of the membranes, and this generator extracts the strain energy work from the membrane expansion and generates electrical work.

The overall system is pulsed by an electrical heater to generate the input heat pulse. Currently, the system has a resonant frequency that is in the low kilohertz regime, but operations under a dynamic damping have demonstrated operation at resonance and the existence of an open mechanical cycle of heat addition, expansion, and heat rejection. Power generation of direct thermal-to-electrical conversion show a 1.45W, 6mJ heat pulse can generate a 0.8 μ W power output pulse, and continuous operation generates a sustained power output of 0.8 μ W at 240Hz. Future improvements in the device will allow active heat rejection, allowing resonance with external damping to improve the thermal to electrical power efficiency.

Contents

Abstract	3
Contents	5
Introduction	6
Background	6
Fabrication	7
Micro Heat Engine Characterization Results.....	8
Conclusions.....	10
References.....	12

Introduction

This LDRD was used to fund the research of a graduate student, Scott Whalen, at Washington State University. The research was on the development of a miniaturized heat engine that would use waste heat from a primary system to generate small amounts of electronic grade power. The principle of operation of this engine was to use a two phase (liquid and gas) working fluid trapped between two deformable membranes in a cavity. During the addition of heat, the ratio of gas to liquid within the working fluid would increase, and the expansion of the gas would deform the membranes outward from the cavity. The restoring force from the membranes provided a compression stroke for the engine after heat was removed, forcing the gas back into a liquid phase by forcibly changing the volume, with the rejected heat being removed from the system through a contact to a heat sink. These expansion and contraction cycles would be converted into electrical power through a series of piezoelectric elements printed on the membranes and wired to an external circuit.

The student worked on this project for three years as part of his PhD. During this time, several papers were published which detailed the operation of this engine in terms of efficiency of operation and comparisons to an idealized stirling cycle for this engine. This report summarizes the major findings of the work. A more complete treatment of the work can be found in the literature publications from this work.^{1 2 3}

Background

There is a pressing need for high energy density micro power generation systems. The energy densities of existing electrochemical batteries are too low (around 1 kJ/g) to sustain the power needs of MEMS devices for long periods.⁴ An attractive alternative to batteries are hydrocarbon fuels, currently the most successful means to transport and store energy compactly. A typical liquid hydrocarbon fuel holds around 50 kJ/g in its chemical bonds.⁵ However, the development of a micro-scale device that can efficiently convert this chemical energy into useful electrical power is challenging. Among the micro-scale concepts to generate electrical power using the chemical energy of hydrocarbon fuels now being explored are fuel cells, static heat engines and dynamic heat engines.

On the macro-scale, dynamic heat engines have achieved greater success than either fuel cells or static heat engines. This success is largely due to dynamic heat engines being more fuel flexible than fuel cells and having achieved higher conversion efficiencies than static heat engines. For these reasons, a variety of designs for micro-scale dynamic heat engines have been advanced. These include a gas turbine (Brayton cycle) engine,^{6 7} a micro rotary internal combustion (Otto cycle) engine⁸ and a micro heat engine based combustion driven reciprocating liquid piston (Otto/Diesel cycle)⁹. All of these dynamic heat engines are internal combustion engines.

Work at Washington State University has been directed toward the development of a MEMS power system based on a dynamic heat engine that is driven by an external heat source, the P³ micro heat engine¹⁰. Since micro-manufacturing methods excel at producing many identical copies of two-dimensional structures, the engine design is a modular, two-dimensional architecture. The P³ micro engine produces electrical power by employing a three-part strategy. First, thermal power is conducted into the P³ engine from an external heat source. Second, thermal power is converted to mechanical power through the expansion and compression of a two-phase working fluid. Third, mechanical power is converted into electrical power through the use of a thin-film piezoelectric generator.

In this summary, the design and fabrication of a prototype P³ micro heat engine is briefly described. A complete treatment may be found in previous work.¹ Special attention is paid to the key component of the engine, the piezoelectric membrane generator. Finally, the results of a study to characterize the operation of the micro heat engine and its membrane generator are presented. For the first time, the production of electrical power by a dynamic micro heat engine is demonstrated.

Fabrication

A prototype unit-cell heat engine is fabricated of three components: a silicon membrane with thin-film piezoelectric generator, a middle spacer in which the engine cavity is defined, and a silicon membrane with resistance heater. A two-phase mixture of the working fluid fills the engine cavity. The piezoelectric material used in the thin-film

membrane generator is lead zirconate titanate (PZT). Figure 1 shows a cross-section of a prototype engine.

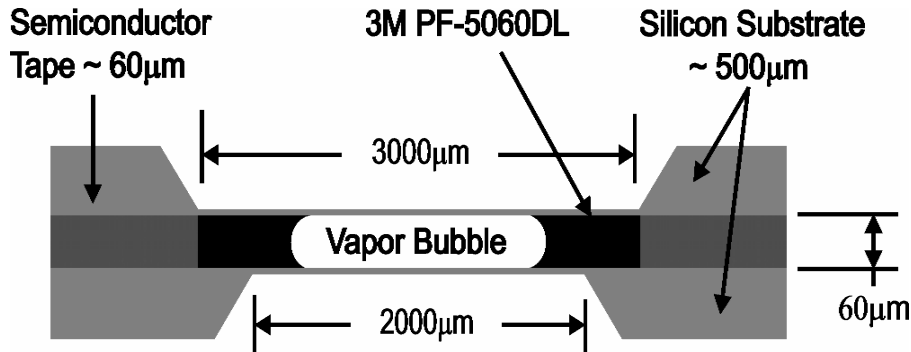


Figure 1: Cross section of the P3 microengine. The cavity is formed by facing thin silicon nitride membranes.

Micro Heat Engine Characterization Results

Dynamic characterization of the micro heat engine is performed by electrically pulsing the resistance heater on the engine's heater membrane to periodically heat the two-phase working fluid. A square wave with a controllable frequency, pulse width, and voltage amplitude is used to energize the heater. The frequency of the square wave determines the engine's cycle speed. The temporal width of the square wave determines the length of the heat addition process in the engine cycle. The voltage amplitude of the square wave determines the heat transfer rate or thermal power into the engine.

The engine was operated using a square wave with a pulse width of 1 millisecond and voltage amplitude of 3.2 volts. Based on a heater resistance of 1.7 ohms, the average power delivered by the resistance heater was 1.45W. The thermal energy delivered to the engine during each heating pulse was 6.02 millijoules.

The electrical output of the membrane generator was measured as the micro heat engine was driven over a range of frequencies. Figure 2 shows the open-circuit peak-to-peak voltage produced by the membrane generator as a function of the engine cycle frequency. The plot shows a resonant peak with the resonant frequency of the micro engine seen to be near 240 Hz.

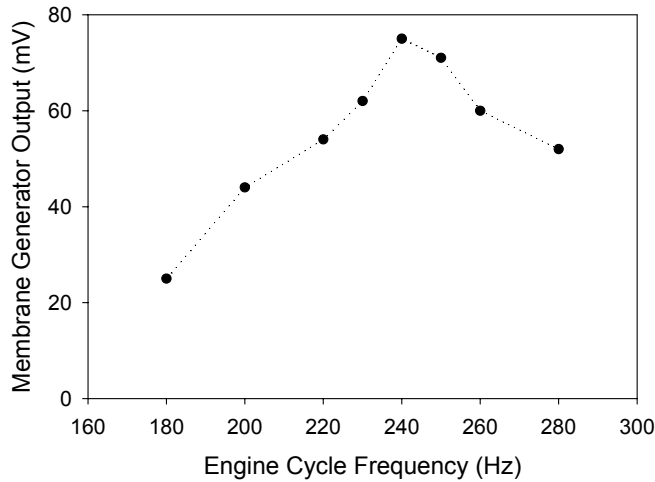


Figure 2: Generator output as a function of frequency. A resonant mode is visible at 240 Hz.

The interferometer was used simultaneously to measure instantaneous heater membrane deflection at equal phase angle intervals of 22.5 degrees (0.26 millisecond time intervals) over the working cycle. Employing the static pressure-deflection curve calculated previously, the dynamic engine pressure was determined. Figure 3 shows the result. Engine pressure is seen to range from a minimum of 26 kPa to a maximum of 38 kPa.

Note that the peak of the membrane generator voltage trace lags the peak of the engine pressure by approximately one millisecond. A one millisecond time lag in a 4.2 millisecond engine cycle represents a phase lag of just under 90 degrees. Since the voltage produced by a membrane generator is a monotonically increasing function of membrane deflection, the peak in voltage must coincide with the peak in membrane deflection. As a result, the peak membrane deflection lags the peak engine pressure by about 90 degrees as expected for resonant operation of the micro heat engine.

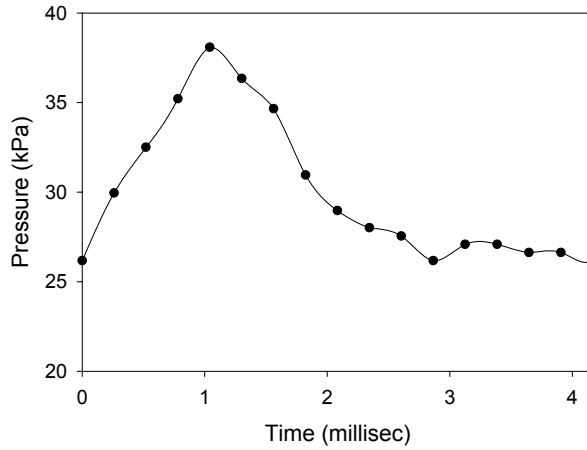


Figure 3: Pressure response in the cavity as a function of time after a heat pulse.

The power produced by the prototype micro heat engine can be determined by dissipating the electrical output from the membrane generator across a load resistance. A decade resistance box is used to match the generator impedance. Figure 4 shows the power produced versus load resistance. A peak power of 0.8 microwatts is seen at a load resistance of 14 kilohms.

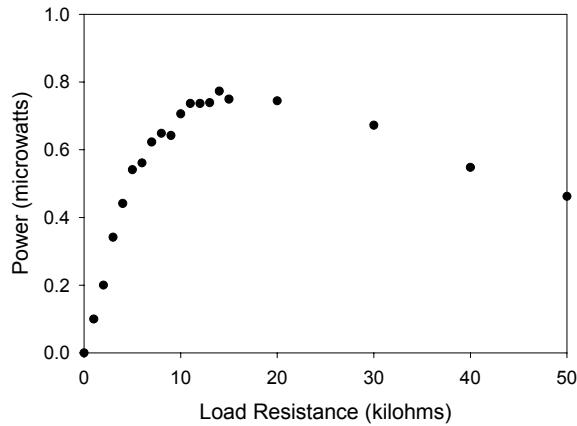


Figure 4: Power output from the piezoelectric generator as a function of external load. Peak power is 0.8 μ W, delivered at an external load of 14kOhms.

Conclusions

The design, fabrication and testing of a micro heat engine has been presented. The design is well suited to photolithography-based batch fabrication methods, and is unlike

any conventionally manufactured macro-scale engine. The prototype micro heat engine is an external combustion engine, in which thermal power is converted to mechanical power through the use of a novel thermodynamic cycle. Mechanical power is converted into electrical power through the use of a thin-film piezoelectric membrane generator. Facilities developed to characterize the performance of the piezoelectric membrane generators and the micro heat engines have been described. The results of a study to characterize the operation of the micro heat engine and its membrane generator have been documented. For the first time, the production of electrical power by a dynamic micro heat engine has been demonstrated. The student at Washington State University has published numerous papers on various aspects of this work, and these papers can be found in the literature.^{1 2 3}

References

- ¹ Whalen, S. A., Thompson, M. R., Richards, C. D., Bahr, D. F., Richards, R. F. Proceedings of IMECE '02, New Orleans (2002).
- ² Whalen, S. A., Weiss, L. W., Richards, C. D., Bahr, D. F., Richards, R. F. Proceedings of the 2003 ASME International Mechanical Engineering Congress and Exposition, Washington, DC (2003).
- ³ Whalen, S., Thompson, M., Bahr, D., Richards, C., Richards, R. Sens. Actuators A, Vol 104 (2003) 290-298.
- ⁴ Land Warrior Power Requirements, Institute of Defense Analysis, U.S. Army Soldier Systems Center, Natick, MA (2000).
- ⁵ R.A. Strehlow, Combustion Fundamentals, McGraw-Hill, New York (1984).
- ⁶ A.H. Epstein, et al., Micro-Heat Engines, Gas Turbines and Rocket Engines - The MIT Microengine project, Proceedings of the 28th AIAA Fluid Dynamics Conference, Snowmass, Colorado (1997).
- ⁷ A. Mehra, X. Zhang, A.A. Ayon, I.A., Waitz, M.A., Schmidt and C.M. Spadaccini, A Six-Wafer Combustion System for a Silicon Micro Gas Turbine Engine, J. MEMS, Vol.9, No. 4 (2000).
- ⁸ K. Fu, A.J. Knobloch, F.C. Martinez, D.C. Walther, C. Fernandez-Pello, A.P. Pisano, D. Liepmann, Design and Fabrication of a Silicon-Based MEMS Rotary Engine, Proceedings of the ASME IMECE 2001, Paper No. MEMS-23925, New York (2001).
- ⁹ W. Yang, Liquid Piston Chip Engine, Proceedings of the DARPA/MTO MEMS/MPG/NMASP Principal Investigators' Meeting, Bloomington, CO, (2001).
- ¹⁰ C-G.Xu, J.Hall, C. Richards, D. Bahr, R. Richards, Design of a Micro Heat Engine, Proceedings of the ASME IMECE, MEMS-Vol.2 (2000) pp.261-268.

DISTRIBUTION:

# of copies	MS	Name
3	0603	Christopher Applett, 1763
1	0603	W. Kent Schubert, 1763
1	1077	Tom E. Zipperian, 1740
1	0123	LDRD Office, 1030
1	9018	Central Technical Files, 8945-1
2	0899	Technical Library, 9616
2	0612	Review and Approval Desk, 9612 For DOE/OSTI